

Impacts of coastal reclamation on wetlands: Loss, resilience, and sustainable management

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ABSTRACT

Coastal wetlands are some of the most valuable ecosystems on Earth because they provide many ecological services for coastal security. However, these wetlands are seriously threatened by accelerated climate change and intensive anthropogenic activities. To understand the impacts of land reclamation on landscape change of coastal wetlands and the long-term effects of disturbances of coastal wetlands on their sustainable management, we used time-series Landsat imagery with an object-oriented classification and Digital Shoreline Analysis System to map wetland changes within a reclaimed area in the Pudong District (PD), in Shanghai, China. Our analysis indicated that from 1989 to 2013, 19,793.4 ha of coastal wetlands have been changed to inland wetlands enclosed by a seawall and dike since 1989, thereby cutting off the exchange of sediment and water flux between the wetlands and the coastal ocean. Subsequently, under the increasing threats of anthropogenic activities, the wetland ecosystem collapsed sharply, in a transformation chain of inland wetland (fresh swamp), artificial wetland (agriculture and aquaculture wetland), and non-wetland (urban land). Under this explosive utilization following coastal reclamation, only 8.9% of natural wetlands remain in the reclaimed area, which has experienced an average annual wetland loss rate of 3.8% over the past 24 years. More than 80% of the wetlands have been developed for agricultural, industrial, and urban land uses, leading to an enormous loss of associated ecological services—benefits arising from the ecological functions provided by wetland ecosystems, thereby undermining the coastal protection these wetlands provided. Nevertheless, considerable regeneration of wetlands occurred because of their inherent resilience. This paper addresses the importance of maintaining a balance between economic growth and coastal ecological protection for sustainable management. It proposes a strategy for how ecosystem-based land planning and ecological engineering should be applied to ensure the effective and sustainable management of living shorelines so that the benefits of healthy ecological functions accrue to coastal ecosystems.

1. Introduction

The coastal zone is the most populous and dynamic region in the world—a trend that is fast becoming more significant under the rapid pace of urbanization. Approximately 65% of the world's big cities with populations over 5 million are located in coastal zones (McGrath et al., 2007). Coastal wetlands, located in transitional zones between the land and the sea, are an important ecological component of the coastal environment, and provide vital habitats for native wildlife. These coastal ecosystems are also crucial for human welfare because they provide hydrological, biogeochemical, and ecological services (e.g. water purification, nutrient cycling, carbon sequestration and coastal protection), as well as socioeconomic benefits (e.g. tourism, recreation, education and research) (Barbier et al., 2011; Mcleod et al., 2011; Scott

et al., 2014; Turner and Daily, 2008). Ecological security, maintaining the buffer zone and mitigating the local biogeochemical cycle, are therefore essential to the human beings living in coastal zones. However, environmental changes as a result of global climate change and human activities stress in coastal wetlands, especially coastal marshes and mangroves, because of their vulnerability to disturbances (Alvarez-Rogel et al., 2007; Crain et al., 2009; Lee et al., 2006; Lee and Yeh, 2009; Nicholls and Cazenave, 2010; Webb et al., 2013).

Among the anthropogenic impacts on coastal wetlands over the short term, land reclamation is a key negative factor that leads to coastal wetland loss and degradation (Tian et al., 2016). To promote economic development in coastal zones, reclaiming tidal wetlands for ports, industry, residences, aquaculture, and agriculture has been a common practice in the coastal region of many countries (Tian et al.,

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2016). Reclamation projects include construction of seawalls and filling or destruction of salt marshes and tidal flats to support economic development. Coastal reclamation causes a number of ecosystem changes, including preventing waves from running up the beach, thereby changing the natural coastal currents and sediment supply to wetlands. Moreover, coastal reclamation also results in a loss of biodiversity and shifts in vegetation structure, composition, and functions; it alters sedimentation, salinity, hydrology, and nutrient inputs; and it introduces artificial structures to wetland environments (Kirwan and Megonigal, 2013; Pendleton et al., 2012; Scott et al., 2014; Zainal et al., 2012).

The construction of seawalls, dikes, jetties, and groins eliminate the tidal influence and directly change coastal and estuarine wetlands to inland wetlands. A more significant impact with devastating effects on reclaimed wetlands are the human-induced disturbances, such as filling, drainage, road crossings, impoundments, groundwater withdrawals, introduced vegetation, and nitrogen inputs from sewage. The majority of coastal wetlands in developing countries are facing enormous losses and degraded ecosystem functions and services because of their excessive use and consumption by humans. With the implementation of opening-up and economic reform policies in the late 1970s, from 1985 to 2010, more than 750,000 ha of coastal wetland have been reclaimed for development in China's coastal zone (Tian et al., 2016). To better manage or rein in this trend, a sustainable strategy for coastal environment management needs to be developed by tracking the historical dynamics of these coastal wetlands.

Since the first launch of the land resource satellite in the 1970s, remotely sensed data have been widely adopted for investigating regional, national, and global resources. Researchers have used remotely sensed data to map wetland change (Ozesmi and Bauer, 2002; Guo et al., 2017). Using a decision tree-based classification, Huang et al. (2009) extracted the data using Landsat imagery to identify the spatial distribution of urban wetlands in Shanghai. Coupling high spatial resolution remotely sensed data (Foremosat-2) with object-oriented classification, Tian et al. (2015) described the wetland conditions and historical trends of 13 types of wetlands in Shanghai from 2003 to 2013 under conditions of rapid urbanization. The historical loss of coastal wetlands owing to reclamation in China has also been delineated with spatial details during the past decades (Tian et al., 2016; Wu et al., 2016).

However, detailed changes concerning human uses of reclaimed wetlands and their impacts on the coastal environment have not been not well addressed in previous work, although huge efforts have been devoted to investigating the spatial and temporal changes in coastal wetlands. Therefore, it is important to evaluate the conditions of reclaimed wetlands to support future ecological restoration efforts in developing countries.

Since the initial launch of the Landsat satellite, more than 40 years of Earth observations have been captured at considerably high spatial and temporal scales. This provides the potential for long-term monitoring of landscape change in coastal zones by catching their dynamic status. This study reported here evaluated the impacts of wetlands reclamation on coastal environment and management in the Pudong District (PD) of Shanghai, China. The PD, as the most active developing and fast-growing district in Shanghai, is subject to high risk related to water security—ability to access sufficient quantities of water resources for industry, agriculture and life (Sun et al., 2016). Time-series Landsat imagery from 1989 to 2013 and geographic information system (GIS) technology were used to identify, evaluate, and analyze the loss of coastal wetlands and the change in reclaimed wetlands before and after seawall and dike construction. The objectives of the study reported here are two-fold: (1) determine the detailed land-use and land-cover change caused by coastal wetlands reclamation; and (2) determine how to achieve an equilibrium between land reclamation and ecological protection in the coastal zones of developing countries.

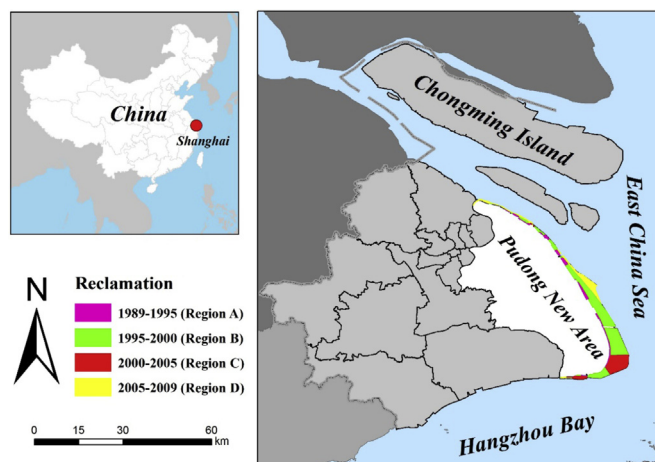


Fig. 1. Location of Pudong District and reclamation from 1989 to 2009. Different colorful patches represent the coastal wetland that were enclosed and reclaimed during the different periods.

2. Study area

Located between the southern bank of the Yangtze River Estuary and the northern bank of Hangzhou Bay (N 30°50'–31°23', E 121°26'–121°59'), the PD is an economically important part of Shanghai (Fig. 1). Because it lies in the mid-low latitude coastal zone, the PD is controlled by a subtropical monsoon climate and has an annual precipitation level of 1233.4 mm and an average long-term temperature of 16.3 °C (Shanghai Statistical Bureau, 2013). Located at the edge of the Yangtze River Delta, the PD takes advantage of the properties of the Yangtze River for economic development. The Yangtze River is the third longest river in the world and the fourth largest river in terms of water discharge and sediment load (Yang et al., 2011). Because of the large flux of sediment from the Yangtze River into the estuary, many coastal wetlands have developed along the shoreline. Moreover, ongoing expansion of coastal wetland is still occurring because of the interaction of the Yangtze River catchment and the ocean. The Yangtze River Estuary is dominated by a semi-diurnal tide that has an average tidal range of 2.66 m. The coastal wetland in the PD is periodically inundated by brackish water. Hence, the coastal wetland in the PD is occupied by three dominant halophytes: *Scirpus mariqueter*, *Spartina alterniflora*, and *Phragmites australis* (Zhao et al., 2009). *Spartina alterniflora* is an exotic species used to improve the rate of deposition in coastal wetlands.

The PD has the largest population and areal extent (5,451,200 people and 1210.41 km² in 2014) of all of the districts in Shanghai (Shanghai Statistical Bureau, 2013). Because of its rapid population and economic growth since the 1990s, the PD has experienced considerable urban expansion compared to its original small-county condition. The enormous demand for land resources has stimulated highly intensive use of various coastal wetlands to maintain the rate of urbanization and industrial development. From 1949, the PD shoreline has moved continuously seaward because of coastal reclamation. In particular, eight reclamation engineering projects have been implemented since 1996 and more than 172 km² of coastal wetland have been reclaimed for agriculture, aquaculture, and urbanization. Additional wetlands will be used in the future according to local land-use plans (LGOSMP, 2015).

3. Materials and methods

3.1. Data source and processing

To detect the wetland change process and transformation trajectory after coastal reclamation related to anthropogenic activities, high-quality time-series archive Landsat images (taken at times of no or little

Table 1
Information from archive landsat images.

Sensor Type	Path/Row	Acquisition Date/Time (GMT+8)	Tidal Level (cm)
Landsat-TM	118/38	1989-08-11 09:52:12	177
Landsat-TM	118/38	1995-08-12 09:28:58	207
Landsat-TM	118/38	2000-06-06 10:01:10	115
Landsat-TM	118/38	2005-08-15 10:14:44	212
Landsat-TM	118/38	2009-07-17 10:14:16	179
Landsat-OLI	118/38	2013-08-13 10:27:24	112

cloudy coverage and relatively low tides) acquired from 1989 to 2013 (Table 1) were downloaded from the United States Geological Survey (USGS) website (<http://www.usgs.gov>). As was done for image pre-processing, geometric correction, atmospheric correction, and image enhancement were performed on all images involved in this research to obtain high-accuracy classification of land covers (Tian et al., 2016).

In the coastal zone, tidal inundation causes the wetlands to become submerged, even with relatively low tide levels. It is also difficult to obtain high-quality images at the lowest tide every year because of the view-obstructing effects of rainy and cloudy weather. Hence, nautical charts were used to delineate the elevation within the intertidal zone to define the types of coastal wetland. The generation of digital elevation models (DEMs) and isobaths of subtidal terrain was implemented in the ArcGIS platform (Li et al., 2016; Tian et al., 2015). In addition, the DEMs and isobaths of the terrain were corrected by elevation ground control points by which elevations were measured using the real-time kinetic global positioning system.

3.2. Reclamation identification and shoreline change analysis

The primary indicators of coastal reclamation are dikes or seawalls in a coastal zone. To identify the historical coastal reclamation of the study area, we selected dikes and jetties as indicators of the shoreline as interpreted from remote-sensing images. Moreover, the shape, location, and optical features of the dikes and jetties differ with respect to the water, soil, and vegetation. Therefore, we employed the normalized differenced water index (NDWI), normalized differenced building index (NDBI), and normalized differenced vegetation index (NDVI) to distinguish the shoreline from other land covers (Tian et al., 2016; Xu, 2007). Visual interpretations with manual digitalization of the shorelines observed on the remote-sensing image were used to detect shoreline changes in the PD using the ArcGIS software. The ground points surveyed in 2013 were used to evaluate the accuracy of the shoreline interpretations.

In this study, reclamation intensity is represented by the change in or movement of the shoreline. The Digital Shoreline Analysis System (DSAS, version 4.3) developed by the USGS was used to calculate the rate of shoreline change or movement. The shoreline in 1989 was used as a baseline to calculate the rate of shoreline change. A series of transects perpendicular to the baseline were generated by the DSAS with equal intervals of 100 m along the shoreline. The intersection of transects as mapped for the baseline and shoreline change conditions, was used to calculate the historical rate of shoreline movement. To acquire the average rate of shoreline movement, the end point rate was used to calculate the rate of shoreline change, and only the oldest and the newest shoreline locations were considered. This process is more suitable for an analysis of shoreline changes over short or moderate time scales (several years to decades). To present the detailed change in spatial scale, the unit of meters per year (m/y) was used in the final result. The negative value indicates the landward direction and the positive indicates the seaward direction.

3.3. Wetland change detection and validation

To track the process of wetland transformation that occurs after

reclamation, an object-oriented classification with multi-resolution segmentation using multi-temporal images was adopted; it delineates the change in the reclaimed wetland by every patch of reclaimed wetland in the PD (Tian et al., 2015). In this study, a multi-resolution segmentation was performed using historical images to track the detailed changes in every patch of reclaimed wetland using the appropriate shape, color, and scale factors. In addition, auxiliary data from the DEMs were extracted from nautical charts and topographical maps to improve the accuracy of the segmentation in the intertidal wetland, which was inundated in the images.

A multi-level hierarchical classification was used to manage the complexity of the land covers in the reclaimed wetlands that are being rapidly developed. The land objects were classified into 11 types: intertidal mudflat, intertidal saltmarsh, estuarine water, fresh swamp, riverine wetland, constructed wetland, built-up area, agricultural land, forest land, unused land, and deep-water area. To specify the features of the objects, thematic remote-sensing indices, such as the NDVI, NDBI, and NDWI (Xu, 2007), were used in the classification as the thematic layers. Based on the framework and rules of hierarchical classification, the types of land covers and wetlands were mapped by the nearest-neighbor classification. To ensure that the classification was spatially accurate and attributes were correctly identified, field survey data were used to assess the accuracy of each classification. In our study, 360 ground truth points were investigated in 2013 to validate the classification.

4. Results

4.1. Coastal reclamation

The coastal reclamation that occurred along the PD shoreline was of high intensity from 1989 to 2013. Calculated by the DSAS, the rates of shoreline change were analyzed quantitatively and spatially (Fig. 2). Subsequently, 911 transects were generated along the overall shoreline at lengths of 15,000 m. The average rate of shoreline change was 136.6 m/y for the entire region from 1989 to 2013, which means that the area moved toward the sea by more than 130 m. The maximum rate of reclamation was 468.0 m/a (excluding abnormal value caused by bended shoreline). The minimum rate was 0 m/a, because all coasts are buffered by hard construction, such as dikes, jetties, and seawalls, which indicates that the associated dikes had not been breached for restoring the reclamation area to wetlands in recent decades. Furthermore, abundant sediment load from the Yangtze River also caused significant deposition in the intertidal zone. Therefore, the shoreline in PD has been moving seaward.

4.2. Landscape change in different reclaimed areas

The reclaimed wetlands in the PD can be divided into four regions based on the reclamation events that happened in 1989–1995, 1995–2000, 2000–2005, and 2005–2009 (represented by region A, B, C, and D, respectively). There was no reclamation in 2009–2013. The variety of land covers are represented by the different colors in different time periods. Four reclaimed regions are represented by the time period during which the reclamation was implemented (Fig. 3). Moreover, although no reclamation occurred in 2009–2013, the landscape change in this period is also discussed.

The total area of region A was originally 1942.0 ha. In 1989, the primary land cover was coastal wetland, including intertidal saltmarsh, estuarine water, and intertidal mudflat, which had areas of 1137.9 ha, 283.8 ha, and 458.1 ha, respectively. A sharp decrease in coastal wetland land area was observed in 1995—more than 70% of the coastal wetlands transformed into other types of land cover. In addition, part of natural wetlands were changed to human-related land-cover types—mostly agricultural land and constructed wetland, which had areas of 126.2 ha and 515.8 ha, respectively. Moreover, because of

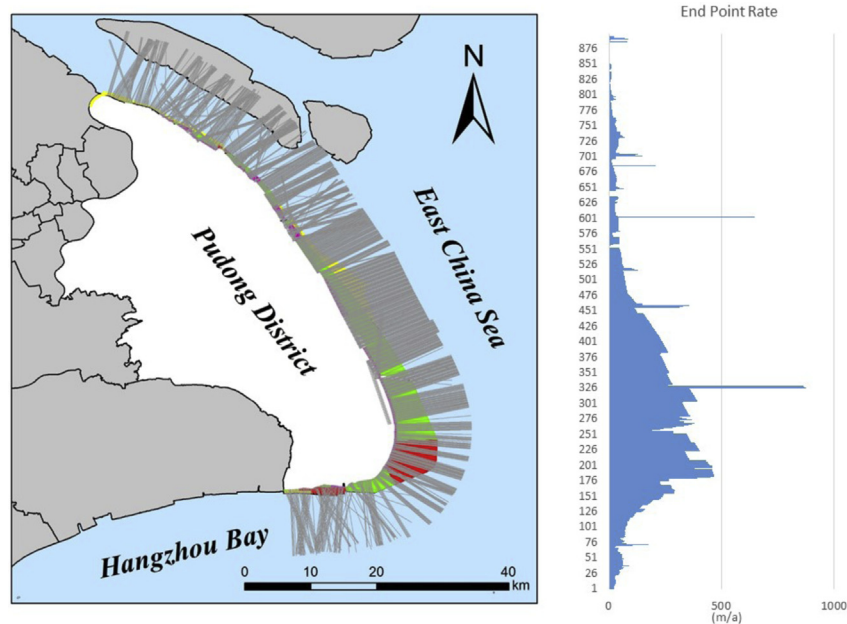


Fig. 2. Reclamation and transect along the shoreline in Pudong District. The number of transects are coded from south to north as shown on y-axis in the histogram (1–900) and the annual rate of reclamation in each transect is shown on the x-axis. * Abnormal high value in right subfigure is caused by bending coastline.

reclamation, 437.4 ha of coastal wetland dried out and was transformed into unused land. In 2000, coastal wetlands only accounted for 6.7% of the study area. Meanwhile, the percentage of agricultural land and constructed wetland continued to expand. After the first appearance of built-up area and forest land in 1995, their areas increased from 65.0 ha to 743.9 ha and 50.1 ha–509.1 ha, respectively. However, from 2000 to 2013, a considerable amount of the agricultural land, constructed wetland, and unused land area was converted to other land uses.

The area of region B was the largest in all of the reclamation periods; it had an area of 11,319.7 ha. A distinct increase in intertidal saltmarsh from 843.5 ha to 1953.2 ha occurred from 1989 to 2000. However, the estuarine wetland simultaneously decreased from 5691.6 ha–801.8 ha at an annual rate of 7.8%. In the reclamation period from 1995 to 2000, more than 4000 ha of intertidal mudflat were lost and transformed into other land uses. After a highly intensive reclamation period, the area of forest land, built-up area, and agricultural

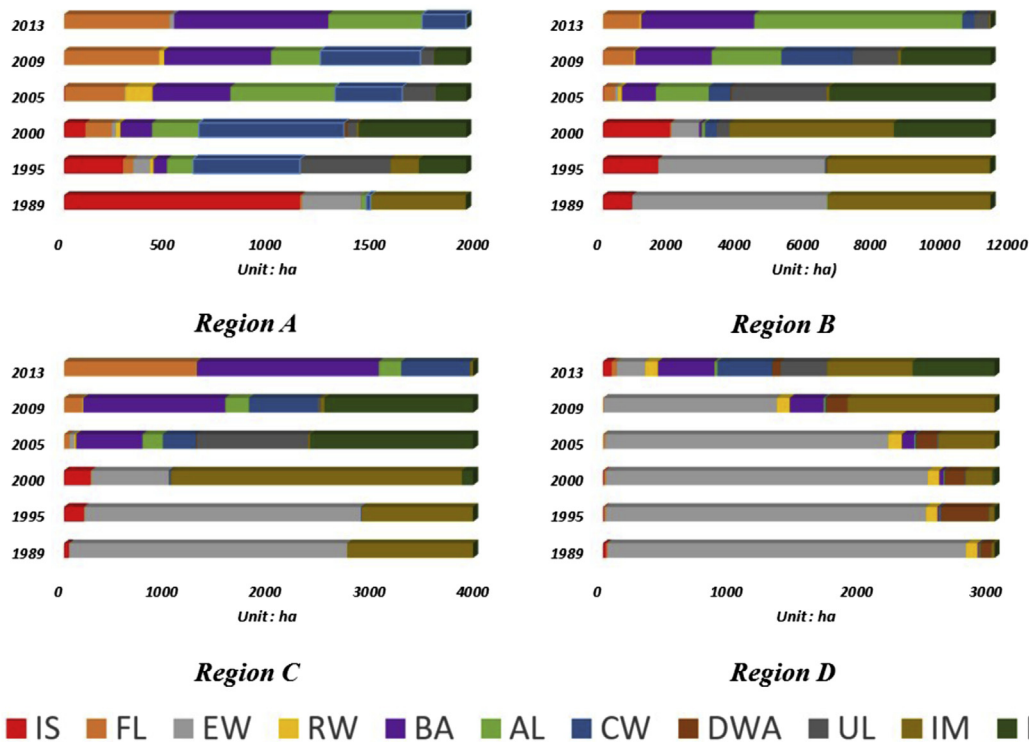


Fig. 3. Dynamic proportion of different land covers in four parts of reclaimed wetland. The types of landscape include intertidal saltmarsh (IS), forest land (FL), estuarine water (EW), riverine wetland (RW), built-up area (BA), agriculture land (AL), constructed wetland (CW), deep water area (DWA), unused land (UL), intertidal mudflat (IM), and freshwater swamp (FS).

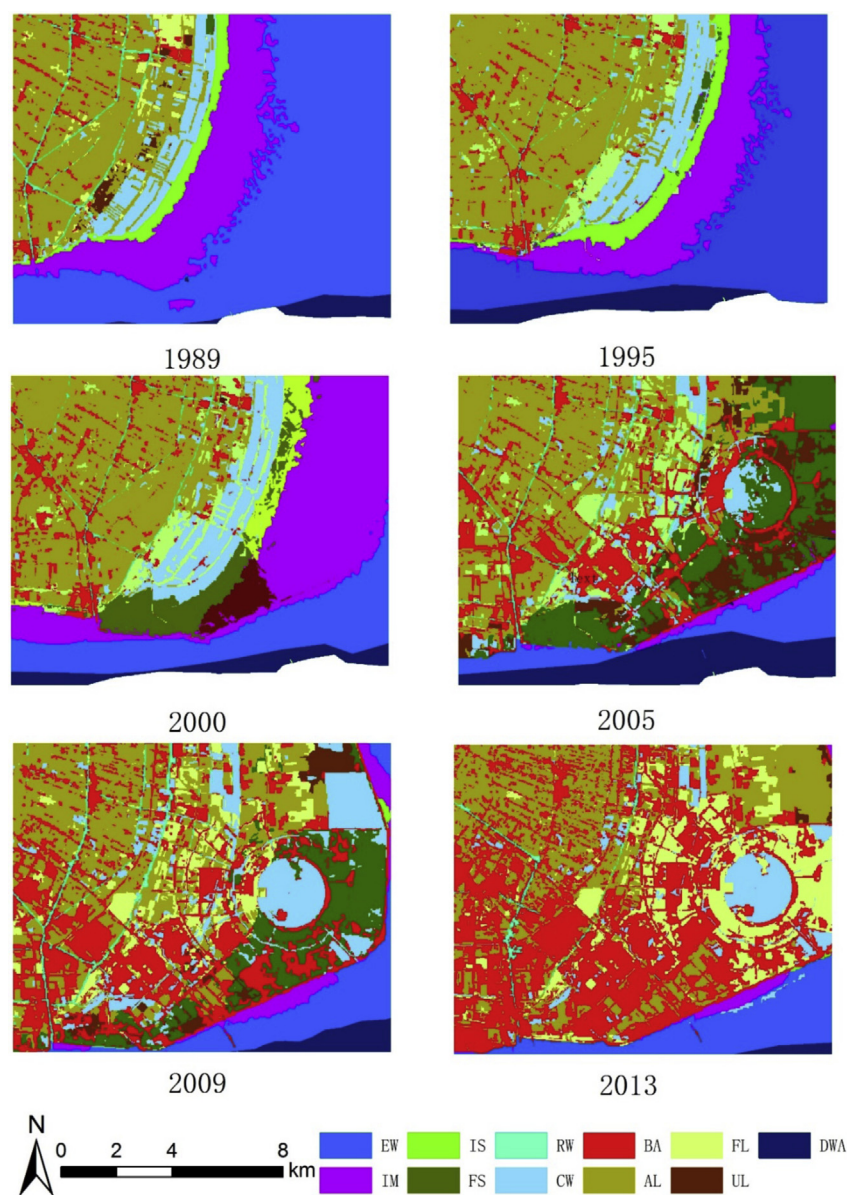


Fig. 4. Landscape and environmental change in Pudong District under the highly intensive reclamation from 1989 to 2013. The types are showed in figure including intertidal saltmarsh (IS), forest land (FL), estuarine water (EW), riverine wetland (RW), built-up area (BA), agriculture land (AL), constructed wetland (CW), deep water area (DWA), unused land (UL), intertidal mudflat (IM), and freshwater swamp (FS).

land developed rapidly. In 2013, the primary land cover was agricultural land, which accounted for 53.7% of the area, and the second greatest land cover was built-up area, which had an area of 3296.2 ha. From 1989 to 2000, the intertidal mudflat area was stable. Nevertheless, after 2000, nearly all of the intertidal mudflat area in the region was lost.

In region C, 3439.5 ha of coastal wetland were enclosed and transformed into land for urbanization. The detailed spatial distribution of historical LUCC is also showed in Fig. 4. A slight increase in intertidal saltmarsh occurred from 1989 to 2000. However, a rapid evolution of coastal wetland occurred from 1995 to 2000 as indicated by a sharp decrease in estuarine and an abrupt increase in intertidal mudflat, and 1934.2 ha of estuarine wetland were converted to intertidal mudflat. After reclamation, this region developed rapidly as an urban area. The area of forest land increased from 51.9 ha to 1277.36 ha. Similarly, an obvious increase also occurred in the area of built-up area from 640.7 ha to 1277.4 ha. Barely any forest land remained in this area by 2013.

In region D, 3024.9 ha of coastal wetland were reclaimed as upland to meet the need for land for urbanization. From 1989 to 2005, the majority of the land cover was estuarine wetland until the implementation of reclamation. In 2013, the estuarine area decreased from 2769.5 ha–219.3 ha. For the expanded construction of the airport, the area of built-up area increased from 95.7 ha to 437.0 ha in 2013. Wetland areas still remained, although they were influenced by human activities. A great increase in constructed wetland occurred from 2009 to 2013, which increased the area of this land use from 8.1 ha to 424.1 ha.

5. Discussion

5.1. Wetlands loss, resilience, and driving forces

Wetland ecosystems are fragile systems, especially coastal wetland ecosystems, which are sensitive to anthropogenic disturbances and climate change (Ayanlade and Proske, 2015; Goldsmith et al., 2015;

Table 2

The transfer matrix of land covers in the reclaimed area of Pudong District (1989–2013)*

(Unit: ha).

	IS	FL	EW	RW	BA	AL	CW	DWA	UL	IM	FS	Total
IS			65.5							1.9		67.4
FL	512.2	8.0	1364.9	4.5	0.3	8.3	10.9	0.1		985.2		2894.3
EW			205.4					14.8				220.1
RW	17.5	0.0	61.6	75.9	0.0	0.6				13.9		169.5
BA	723.9	12.8	2772.6	10.7	11.4	9.8	8.3	0.9	0.2	2316.5	2.8	5869.8
AL	441.4	3.5	3640.8	0.1		8.2	4.6			2652.6	0.7	6751.8
CW	164.3		1162.8	0.6		0.1	2.5			316.3		1646.6
DWA			35.9					29.6				65.5
UL			694.5							109.5		804.0
IM	0.0		626.0					41.3		3.8		671.1
FS			633.3									633.3
Total	1859.2	24.2	11263.2	91.8	11.7	27.0	26.3	86.6	0.2	6399.6	3.5	19793.4

*Abbreviation of land covers in table: intertidal saltmarsh (IS), forest land (FL), estuarine water (EW), riverine wetland (RW), built-up area (BA), agriculture land (AL), constructed wetland (CW), deep water area (DWA), unused land (UL), intertidal mudflat (IM), and freshwater swamp (FS).

Mcgranahan et al., 2007; Morris et al., 2002; Schuyt, 2005; Webb et al., 2013). Human-induced wetland loss is the primary factor affecting wetlands over the short term (from several years to decades). From 1989 to 2013, a significant part of wetlands were reclaimed and destroyed by direct human use and modification in the PD (Table 2). Nevertheless, if reclamation is implemented in suitable locations (i.e., at specific elevations) and at acceptable rates, coastal wetlands could be regenerated and recovered outside the reclamation dike because of the abundant sediment loads from the Yangtze River catchment (Dai et al., 2014). This study showed that a distinct increase in intertidal saltmarsh occurred in the second reclaimed period from 1989 to 2000 because of the reclamation of intertidal mudflat in the first reclaimed area (Fig. 3). Similarly, increases in intertidal saltmarsh and intertidal mudflat occurred in the third period after the reclamation of the second period (Fig. 3). However, under the current policies and strategies in PD of Shanghai (LGOSMP, 2015), it is unlikely to transform human-related land cover to natural wetlands. Therefore, as an integrated system, coastal wetlands shows their resilience to reclamation by the regeneration of intertidal wetlands outside dikes (i.e. intertidal saltmarsh and intertidal mudflat) to keep their primary ecosystem services in coastal defenses and habitats provision for water birds, surviving in the other location of the coastal or estuarine ecosystem from human-induced wetland loss. As coastal wetlands ecosystem respond to sea level rise (by accelerating the vertical accretion to survive from sea level rise) (Morris et al., 2002), coastal wetlands develop horizontally in the seaward direction to survive from coastal reclamation by the abundant sediment input from Yangtze River.

However, coastal wetland ecosystem cannot survive from intensive coastal reclamation, just as it cannot from extreme high sea level rise rate (Kirwan et al., 2010). After the construction of the dike, the wetland was rapidly transformed into other land uses, which indicates that the wetlands were destroyed by direct human modification (Kirwan and Megonigal, 2013; Tian et al., 2015). Because of the close relationship between reclamation and governmental policies, the wetland areas reclaimed in the PD during different periods were designated for specific land-use planning purposes. In the first period of reclamation (1989–1995), an international shipping center was constructed in region A, and most of the reclaimed wetlands were transformed into wharfs and depots. Most of the land cover in this area consisted of forest land and built-up area in 2013, which reflects the construction of a well-developed harbor area. In addition, the harbors were constructed densely in the northern part of the PD along the shore (Fig. 2), because, although they do not require abundant space, they must be located on a long shoreline. Compared with the requirements for a harbor, areas designated for urbanization, agriculture, and aquaculture all require considerable space for development and have been located in the southern part of the PD (Fig. 2). From 1995 to 2000, the rapid

expansion of the central urban area corresponded to a significant increase in the transformation of agricultural land near the central urban area to built-up area (Han et al., 2009; Zhao et al., 2003). To maintain sufficient agricultural land to satisfy the demand for food, a considerable amount of wetlands was enclosed and reclaimed for agriculture and aquaculture during this period (Tian et al., 2015). More than 50% of the land cover in this area was agricultural land in 2013. During the third period of wetland reclamation, the continuous expansion of urbanization required municipal government development of a new region to mitigate the pressure caused by the rapid population growth (Zhao et al., 2003). Therefore, a well-planned satellite city was built in the reclaimed area from 2000 to 2005. Nearly 80% of the area in this region consisted of built-up area and forest land in 2013. From 2005 to 2009, wetlands in this area were reclaimed for the Pudong International Airport expansion, which required land-cover types similar to those in suburban regions. Therefore, direct human use was the main cause of wetlands loss from 1989 to 2013.

Direct modification by human-driven policies enacted by the municipal government is the primary cause of the dramatic loss of wetlands in the PD. Under the influence of high-intensity modifications, the coastal wetlands outside the dike cannot recover naturally. The unlimited exploitation of these wetlands leads to their significant loss in the PD, instead of their sustained existence as a resilient wetland ecosystem.

5.2. Function and structure change of wetland ecosystem

Direct human actions on coastal wetlands alter the structure and biogeochemical processes of wetland ecosystems, resulting in a serious loss or degradation of wetlands functions and services, which threatens catastrophic effects on coastal ecological security (Briassoulis, 2015; Cui et al., 2015; Kirwan and Megonigal, 2013; Mcgranahan et al., 2007; Schuyt, 2005). The coastal wetlands in the PD, mainly consisted of intertidal saltmarsh and mudflat, are key components of coastal defenses and natural habitats for water birds. However, with the rapid urbanization, the majority of coastal wetlands were transformed into human-related land cover from 1989 to 2013, which eliminated wetland ecological functions in the reclaimed area. Interestingly, a specific trajectory can be used to describe the landscape of coastal wetlands induced by reclamation (Figs. 4 and 5). In the transformation of landscape in coastal wetlands, the continuously increasing influence of human activities causes direct and indirect disturbances to the biogeochemical processes related to hydrology (e.g. tidal current), geomorphology (e.g. sediment deposition), and ecology (e.g. vegetation zonation, in Yangtze Estuary *Phragmites australis* at high marsh, *Spartina alterniflora* at the middle and *Scirpus mariqueter* at lower marsh) (Barbier et al., 2011; Tian et al., 2016). Because of excessive human



Fig. 5. The trajectory of wetland transformation in Shanghai. From the natural wetland to the built-up area, there are four different stages (a) Coastal wetland, connecting to coastal ocean, dominated by salt or brackish water; (b) inland fresh swamp, enclosed by seawall and dike, dominated by freshwater; (c) agriculture and aquaculture land; and (d) built-up area, covered by an impervious surface.

interference, wetlands and the associated ecosystem services are continuously decreasing, even disappear because of irreversible modifications to the land, resulting in direct exposure of the city to coastal disasters and complete loss of habitats for water birds.

In their initial status, coastal wetlands (e.g., intertidal saltmarsh, intertidal mudflat) directly connect to coastal oceans and estuaries, and the wetland ecosystems are periodically flooded with brackish water. The dominant species of the wetlands in the study area include the halophytes *Scirpus mariqueter*, *Spartina alterniflora* and *Phragmites australis*. Because of the high productivity and unique environment of coastal wetlands, they are among the most valuable ecosystems on Earth (about intertidal saltmarsh \$4291/acre) (Barbier et al., 2011; Kirwan and Megonigal, 2013). However, after reclamation, dikes block the coastal wetlands from the ocean, cutting off the interactions between the land and the ocean, and altering the material transportation, physical conditions, and hydrological processes of the wetland ecosystem. Without the exchange between land and ocean, the wetland ecosystem is controlled by freshwater and the wetland type converts to a freshwater swamp. During this period, although the primary biogeochemical exchange between the wetlands and ocean is cut off, the basic ecosystem functions provided by wetlands are reserved owing to little interference in the structure of the ecosystem (Kirwan and Megonigal, 2013). Moreover, hydrodynamic changes and abundant sediment fluxes to the Yangtze Estuary generate new coastal wetland outside the dike, as indicated by the transformation of estuarine wetland to intertidal mudflat and intertidal saltmarsh. This modification accelerates the evolution of new coastal wetlands and protects the developed freshwater swamps from the impacts of erosion and storm surges.

Over time, the implementation of land planning will transform most of the wetlands to drained land for agriculture and aquaculture, or other specific activities, which will destroy the basic structure of the wetland ecosystem and only provides few ecological services (Berlanga-Robles et al., 2011). Specialized land-use types, such as agricultural and constructed wetland, are used to provide economic products for humans that contribute few ecological services to local environmental security (Costanza et al., 1997). At this period, because of the

destruction of the intrinsic structure and biogeochemical processes of wetland ecosystems, irreversible alteration occurs, causing the loss of natural wetlands. The direct use of freshwater swamps for agriculture and aquaculture alters the landscape structure and biogeochemical processes of wetlands. Meanwhile, part of the wetlands is converted to undeveloped drained land (e.g., agricultural land), which retains only minimal ecological functions and services. Moreover, agricultural land and constructed wetland are reserved land resources that satisfy the requirements of land for rapid urbanization. During the final period, the transformation from agricultural land and constructed wetland to built-up area indicates a permanent loss of wetland functions. The results show that built-up area cannot be converted to other natural land covers under the present land-use planning policies. Water, soil, and vegetation are three important wetland elements that are completely replaced by impervious surfaces, which do not provide ecological functions and cause a series of environmental problems (e.g. heat island).

5.3. Implications for coastal sustainable management

High-intensity reclamation in the PD resulted in an enormous loss of coastal wetlands and weakened the coastal zone's defenses against destructive natural disasters, such as coastal flooding induced by hurricanes and tsunamis (Arkema et al., 2013; Hallegatte et al., 2013; Snoussi et al., 2008; Temmerman et al., 2013; Tian et al., 2015). Urbanization with exploitative development in coastal zones is not consistent with Shanghai's goal to build an ecological city (LGOSMP, 2015). To maintain the high pace of economic growth, a strategy must be proposed to mitigate the conflict between development and environmental issues.

In past decades, the economic development policies instituted in China in the late 1970s (after the reform and opening-up) promoted exploitative development with little consideration of environmental impacts until recent years, and this practice has caused serious environmental problems throughout the country (Niu et al., 2012). Because Shanghai is the center of economic development in China, it has experienced complete changes in its marine environment because of

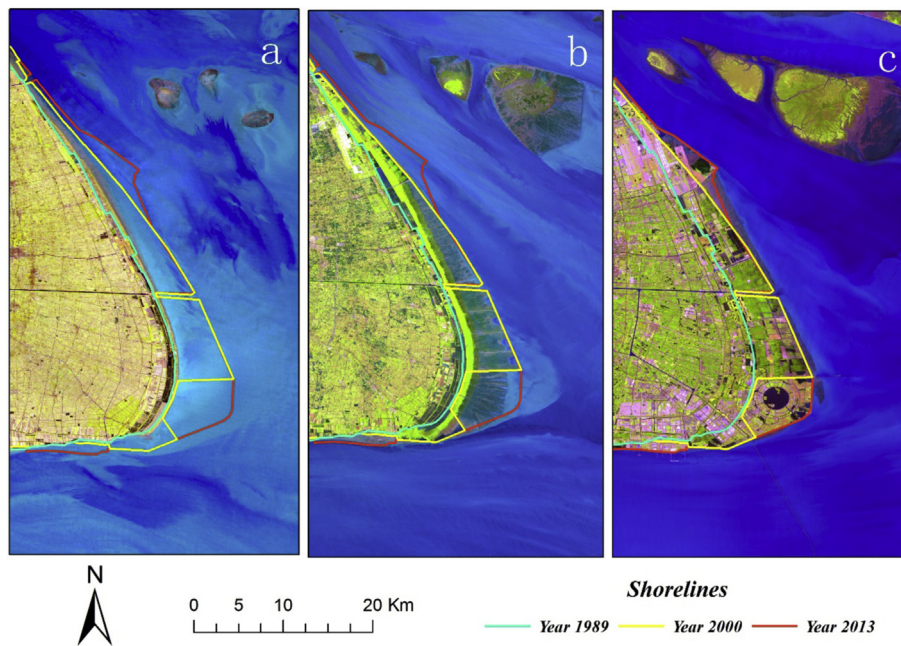


Fig. 6. The change in wetland and shoreline (represented in different colors indicating different years) interpreted from remote sensing images. (a) No dike, jetty, and reclamation existed in 1989 and saltmarshes can be submerged by tidal water; (b) intertidal saltmarshes were enclosed by a dike and jetty, and the tide and interaction between saltmarshes and ocean were blocked by the dike and jetty; (c) the inland freshwater swamp was transformed into land for agriculture, aquaculture, and urbanization, and the construction and processes of coastal wetland ecosystems were completely destroyed by wetland modification by human activities. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

excessive human use and alteration of the coastal wetlands (Fig. 6). A large proportion of the wetlands were exploited by urbanization. Because of the high-intensity reclamation and direct modifications of the wetlands, only a small amount of wetland ecosystems remains, despite the natural resilience and regeneration capabilities of wetlands under less severe circumstances. As a result of exploitive development, the PD coastal zone has almost no natural protection against destructive natural disasters. The most traditional and effective approach to protecting coastal cities after wetland exploitation is to build a high and thick seawall. In contrast, green infrastructure provides an environmentally friendly approach to coping with coastal hazards. However, these two approaches cannot satisfy the needs of economic growth and environmental protection at the same time in many developing countries. In the aftermath of historical land-management planning errors, a balanced ecological strategy should be applied to build an environmentally friendly coastal zone (Peimer et al., 2016). That is, the rate of reclamation should be slowed to match the rate of wetland regeneration in the coastal zone. Also, the loss of ecological services provided by wetland ecosystems needs to be offset by other landscapes or other means under practices of sustainable coastal environmental management.

For coastal protection, a living shoreline constructed using ecological engineering should be implemented to provide a sufficient ecological barrier to buffer the coastal zone from the damage caused by extreme natural hazards (Arkema et al., 2013; Cheong et al., 2013). According to the master plan for land use in Shanghai from 2020 to 2040, the built-up area, which is currently at a peak, should be limited to maintain adequate agricultural land (LGOSMP, 2015). Therefore, an ecological strategy that can maintain the area of coastal wetland and increase the area of agricultural land is proposed in this study. Our study shows that if dikes are built in proper locations (e.g., intertidal mudflat) without excessive, direct modifications of wetland, the evolution of coastal wetlands outside the dike will be accelerated by the abundant sediments load from the Yangtze River catchment. Moreover, native salt marshes will be protected by the open dike (i.e., the dike will not cut off the exchange between the wetland ecosystem and the coastal ocean) and experience little or no loss of ecosystem functions and services. Because of the altered hydrological conditions and abundant sediment load from the Yangtze River, the coastal wetland outside the dike will develop rapidly and generate a new ecological buffer for coastal protection, thereby forming two coastal ecological barriers.

Direct utilization (except for natural ecological modifications) should not occur in the enclosed wetland until the equilibrium of coastal wetlands has been stabilized outside the dike. The enclosed freshwater swamp could be converted to agricultural land or constructed wetland for human uses when the new coastal wetland is large enough to protect the coastal zone. A trade-off tipping point could be found in the non-linear relationship between coastal protection and preserved wetland area to provide maximum ecological and economic value (Barbier et al., 2008).

6. Summary and conclusions

In this study, we used time-series Landsat images, an object-oriented classification method, and a DSAS to analyze land-use and land-cover change and the intensity of coastal reclamation in the PD of Shanghai, China. Long-term and high-resolution landscape changes were mapped with spatial details. The study results showed that, in the Yangtze River Estuary, there was significant movement of shoreline toward the ocean owing to the high intensity of coastal reclamation. Interestingly, because of the abundant sediment load from the river, accelerated seaward evolution of coastal wetland occurred outside the seawalls. The evolution of coastal wetland reveals the resilience of reclaimed wetland ecosystems, which created two ecological barriers for the coastal zone on both sides of the seawalls. However, driven by the huge pressure of rapid urbanization, policy-driven exploitatively direct human use of reclaimed wetlands resulted in the sharp collapse of wetland ecosystems, even though there was considerable deposition of sediment due to the resilience of the natural ecosystem. A transformation chain exists when the enclosed coastal wetlands are used and modified for development. Further quantitative analysis of the change of ecosystem services value and ecosystem resilience with increasing impacts of human activities is necessary in future research.

With the increasing effect of human activities, the structure of coastal wetland ecosystems were destroyed or replaced by a drained and impervious surface. The primary elements of wetlands (i.e., water, soil, and vegetation) were eliminated, which caused serious destruction of the ecological services that they provide. Therefore, to mitigate the conflict between high economic growth and coastal ecological security, an equilibrium between land use and wetlands regeneration were proposed relative to the resilience of the wetland ecosystem. It proposes a strategy for how ecosystem-based land planning and ecological

engineering should be applied to ensure the effective and sustainable management of living shorelines so that the benefits of healthy ecological functions accrue to coastal ecosystems.

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References

- Alvarez-Rogel, J., Jimenez-Carceles, F.J., Roca, M.J., Ortiz, R., 2007. Changes in soils and vegetation in a Mediterranean coastal salt marsh impacted by human activities. *Estuar. Coast Shelf Sci.* 73, 510–526.
- Arkema, K.K., Guannel, G., Verutes, G., Wood, S.A., Guerri, A., Ruckelshaus, M., Kareiva, P., Lacayo, M., Silver, J.M., 2013. Coastal habitats shield people and property from sea-level rise and storms. *Nat. Clim. Change* 3, 913–918.
- Ayanlade, A., Proske, U., 2015. Assessing wetland degradation and loss of ecosystem services in the Niger Delta, Nigeria. *Mar. Freshw. Res.* 67 (6), 828–836.
- Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. *Ecol. Monogr.* 81, 169–193.
- Barbier, E.B., Koch, E.W., Silliman, B.R., Hacker, S.D., Wolanski, E., Primavera, J., Granek, E.F., Polasky, S., Aswani, S., Cramer, L.A., Stoms, D.M., Kennedy, C.J., Bael, D., Kappel, C.V., Perillo, G.M.E., Reed, D.J., 2008. Coastal ecosystem-based management with nonlinear ecological functions and values. *Science* 319, 321–323.
- Berlanga-Robles, C.A., Ruiz-Luna, A., Bocco, G., Vekerdy, Z., 2011. Spatial analysis of the impact of shrimp culture on the coastal wetlands on the Northern coast of Sinaloa, Mexico. *Ocean Coast Manag.*, vol. 54, 535–543.
- Briassoulis, H., 2015. The socio-ecological fit of human responses to environmental degradation: an integrated assessment methodology. *Environ. Manag.* 56 (6), 1448–1466.
- Cheong, S., Silliman, B., Wong, P.P., van Wesenbeeck, B., Kim, C., Guannel, G., 2013. Coastal adaptation with ecological engineering. *Nat. Clim. Change* 3, 787–791.
- Costanza, R., Darge, R., Degroot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., Oneill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., Vandenbelt, M., 1997. The value of the World's ecosystem services and natural capital. *Nature* 387, 253–260.
- Crain, C.M., Halpern, B.S., Beck, M.W., Kappel, C.V., 2009. Understanding and managing human threats to the coastal marine environment. *Ann. N. Y. Acad. Sci.* 1162, 39–62.
- Cui, L., Li, G., Liao, H., Ouyang, N., Zhang, Y., 2015. Integrated approach based on a regional habitat succession model to assess wetland landscape ecological degradation. *Wetlands* 35, 281–289.
- Dai, Z., Liu, J.T., Wei, W., Chen, J., 2014. Detection of the three gorges dam influence on the changjiang (Yangtze River) submerged Delta. *Sci. Rep.* 4, 6600.
- Goldsmith, K.A., Granek, E.F., Lubitow, A., 2015. Information needs assessment for coastal and marine management and policy: ecosystem services under changing climatic, land use, and demographic conditions. *Environ. Manag.* 56, 1502–1513.
- Guo, M., Li, J., Sheng, C., Xu, J., Wu, L., 2017. A review of wetland remote sensing. *Sensors* 17 (777).
- Hallegatte, S., Green, C., Nicholls, R.J., Corfee-Morlot, J., 2013. Future flood losses in major coastal cities. *Nat. Clim. Change* 3, 802–806.
- Han, J., Hayashi, Y., Cao, X., Imura, H., 2009. Application of an integrated system dynamics and cellular automata model for urban growth assessment: a case study of Shanghai, China. *Landsc. Urban Plann.* 91, 133–141.
- Huang, Y., Zhou, Y., Wu, W., Kuang, R., Li, X., 2009. Shanghai urban wetland extraction and classification with remote sensed imageries based on a decision tree model. *J. Jilin Univ. (Earth Sci. Ed.)* 39, 1156–1162 (in Chinese with English Abstract).
- Kirwan, M.L., Guntenspergen, G.R., D'Alpaos, A., Morris, J.T., Mudd, S.M., Temmerman, S., 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophys. Res. Lett.* 37 (23).
- Kirwan, M.L., Megonigal, J.P., 2013. Tidal wetland stability in the face of human impacts and sea-level rise. *Nature* 504, 53–60.
- Leading Group Office of Shanghai Master Plan (LGOSMP), 2015. Outline of Shanghai master plan (2015–2040) (in Chinese). Available on website. <http://www.shgtj.net/news/256>.
- Lee, S.Y., Dunn, R.J.K., Young, R.A., Connolly, R.M., Dale, P.E.R., Dehay, R., Lemckert, C.J., Mckinnon, S., Powell, B., Teasdale, P.R., Welsh, D.T., 2006. Impact of urbanization on coastal wetland structure and function. *Austral Ecol.* 31, 149–163.
- Lee, T., Yeh, H., 2009. Applying remote sensing techniques to monitor shifting wetland vegetation: a case study of danshui River Estuary mangrove communities, Taiwan. *Ecol. Eng.* 35, 487–496.
- Li, X., Liu, J.P., Tian, B., 2016. Evolution of the Jiuduansha wetland and the impact of navigation works in the Yangtze estuary, China. *Geomorphology* 253, 328–339.
- McGranahan, G., Balk, D., Anderson, B., 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ. Urbanization* 19, 17–37.
- McLeod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H., Silliman, B.R., 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO₂. *Front. Ecol. Environ.* 9, 552–560.
- Morris, J.T., Sundareshwar, P.V., Nichol, C.T., Kjerfve, B., Cahoon, D.R., 2002. Responses of coastal wetlands to rising sea level. *Ecology* 83, 869.
- Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. *Science* 328, 1517–1520.
- Niu, Z.G., Zhang, H.Y., Wang, X.W., Yao, W.B., Zhou, D.M., Zhao, K.Y., Zhao, H., Li, N.N., Huang, H.B., Li, C.C., Yang, J., Liu, C.X., Liu, S., Wang, L., Li, Z., Yang, Z.Z., Qiao, F., Zheng, Y.M., Chen, Y.L., Sheng, Y.W., Gao, X.H., Zhu, W.H., Wang, W.Q., Wang, H., Weng, Y.L., Zhuang, D.F., Liu, J.Y., Luo, Z.C., Cheng, X., Guo, Z.Q., Gong, P., 2012. Mapping wetland changes in China between 1978 and 2008. *Chin. Sci. Bull.* 57, 2813–2823.
- Ozesmi, S.L., Bauer, M.E., 2002. Satellite remote sensing of wetlands. *Wetl. Ecol. Manag.* 10, 381–402.
- Peimer, A.W., Krzywicka, A.E., Cohen, D.B., Van den Bosch, K., Buxton, V.L., Stevenson, N.A., Matthews, J.W., 2016. National-level wetland policy specificity and goals vary according to political and economic indicators. *Environ. Manag.* 59 (1), 141–153.
- Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., Sifleet, S., Craft, C., Fourqurean, J.W., Kauffman, J.B., Marba, N., Megonigal, P., Pidgeon, E., Herr, D., Gordon, D., Baldera, A., 2012. Estimating global “blue carbon” emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS One* 7, e43542.
- Schuyt, K.D., 2005. Economic consequences of wetland degradation for local populations in Africa. *Ecol. Econ.* 53, 177–190.
- Scott, D.B., Frail-Gauthier, J., Mudie, P.J., 2014. Coastal Wetlands of the World: Geology, Ecology, Distribution and Applications. Cambridge University Press.
- Shanghai Statistical Bureau, 2013. Shanghai Statistical Bureau. Shanghai Statistical Yearbook. Shanghai Statistical Bureau, Shanghai.
- Snoussi, M., Ouchani, T., Niaz, S., 2008. Vulnerability assessment of the impact of sea-level rise and flooding on the Moroccan coast: the case of the Mediterranean eastern zone. *Estuar. Coast Shelf Sci.* 77, 206–213.
- Sun, F., Kuang, W., Xiang, W., Che, Y., 2016. Mapping water vulnerability of the Yangtze River basin: 1994–2013. *Environ. Manag.* 58 (5), 857–872.
- Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. *Nature* 504, 79–83.
- Tian, B., Wu, W., Yang, Z., Zhou, Y., 2016. Drivers, trends, and potential impacts of long-term coastal reclamation in China from 1985 to 2010. *Estuar. Coast Shelf Sci.* 170, 83–90.
- Tian, B., Zhou, Y., Thom, R.M., Diefenderfer, H.L., Yuan, Q., 2015. Detecting wetland changes in Shanghai, China using formosat and Landsat TM imagery. *J. Hydrol.* 529, 1–10.
- Turner, R.K., Daily, G.C., 2008. The ecosystem services framework and natural capital conservation. *Environ. Resour. Econ.* 39, 25–35.
- Webb, E.L., Friess, D.A., Krauss, K.W., Cahoon, D.R., Guntenspergen, G.R., Phelps, J., 2013. A global standard for monitoring coastal wetland vulnerability to accelerated sea-level rise. *Nat. Clim. Change* 3, 458–465.
- Wu, W., Tian, B., Zhou, Y., Shu, M., Qi, X., Xu, W., 2016. The trends of coastal reclamation in China in the past three decades. *Acta Ecol. Sin.* 36, 5007–5016.
- Xu, H., 2007. Extraction of urban built-up land features from Landsat imagery using a thematic-oriented index combination technique. *Photogramm. Eng. Rem. Sens.* 73, 1381–1391.
- Yang, S.L., Milliman, J.D., Li, P., Xu, K., 2011. 50,000 dams later: erosion of the Yangtze River and its delta. *Global Planet. Change* 75, 14–20.
- Zainal, K., Al-Madany, I., Al-Sayed, H., Khamis, A., Al-Shuhaby, S., Al-Hisaby, A., Elhoussiny, W., Khalaf, E., 2012. The cumulative impacts of reclamation and dredging on the marine ecology and land-use in the kingdom of Bahrain. *Mar. Pollut. Bull.* 64, 1452–1458.
- Zhao, B., Nakagoshi, N., Chen, J.K., Kong, L.Y., 2003. The impact of urban planning on land use and land cover in Pudong of Shanghai, China. *J. Environ. Sci.* 15, 205–214.
- Zhao, B., Yan, Y., Guo, H., He, M., Gu, Y., Li, B., 2009. Monitoring rapid vegetation succession in estuarine wetland using time series modis-based indicators: an application in the Yangtze River Delta area. *Ecol. Indic.* 9, 346–356.